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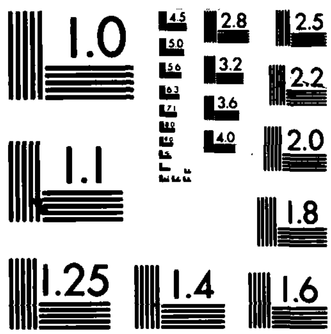

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Techniques for the Automated Observation of Clouds

JAMES I. METCALF

10 October 1985

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ATMOSPHERIC SCIENCES DIVISION PROJECT 6670
AIR FORCE GEOPHYSICS LABORATORY
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FOR THE COMMANDER

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Techniques for cloud detection ~~are surveyed~~ to assess their suitability for meeting the requirements of the Automated Observation System (AOS). A microwave sensor is essential because of the requirements for observing cloud top heights and documenting multiple cloud layers. Wavelengths between 3 cm and 8.6 mm could be used for this application, and a detailed sensor design study is recommended to evaluate the availability, cost, performance, and reliability of components and systems. Pulsed or continuous-wave radars could meet most of the requirements, although measurements of cloud base with high accuracy at low altitude may be difficult with some pulsed systems.

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1. INTRODUCTION

The Automated Weather Distribution System (AWDS) is being developed to automate the acquisition, transmission, analysis, and display of weather information at Air Force base weather stations. A key part of this system is the Automated Observation System (AOS), which is intended to assume, as far as possible, the role of the weather observer. The full observational requirements of AOS include standard weather parameters such as temperature, humidity, pressure, and wind; present weather conditions such as visibility, precipitation of various types, lightning, and severe winds; and sky condition. In this context, we have investigated several techniques for the automated observation of clouds.

In this report, we identify key issues in the design of a cloud sensor, the data processing, and the extraction of observational parameters. We recommend courses of action to develop the detailed design of a cloud sensor and to develop the necessary data processing techniques. The sensor must be capable of measuring the ceiling with required 10-ft height accuracy at low altitude, and must be sufficiently sensitive to detect tenuous clouds. Reliable extraction of cloud bases

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and tops and cloud amount requires the development of a sampling strategy in space and time, involving either multiple sensors, a multiple-beam sensor, or a scanning sensor.

In the context of AOS, the cloud sensing system could be viewed as a component of a comprehensive sensing system in that information derived from other sensors could contribute to the interpretation of data acquired by the cloud sensing system. In this report, however, we address the cloud sensing issue only from the perspective of developing a single sensor or combination of sensors to acquire the cloud measurements. We do not address the complementary issue of using data from the cloud sensing system to infer other weather parameters.

The cloud observation system should enable the automatic specification of those parameters presently recorded by observers, namely, ceiling and cloud amount. Ceiling is usually determined by measurement, for example, with a rotating beam ceilometer (RBC), or by estimation, for example, from pilot reports or balloon ascent. The accuracy of measurements by RBC is depicted in Figure 1, based on a nominal 1-degree beam tracking error and baselines of 400 and 800 ft.[1] For comparison, the TPQ-11 radar used by Air Weather Service (AWS) between 1964 and 1975[2,3] yielded measurements of ceiling with an accuracy of ±187 ft from a facsimile recorder and ±125 ft from the radar A-scope display. Determination of cloud amount includes the identification of cloud layers and the determination of their base heights and their fractional coverage of the sky. The sky cover designator at each layer represents the total fraction of sky covered by that layer and by all lower layers. The height at which the sky coverage is 5/10 or greater constitutes the reported ceiling. A pilot flying at or above the ceiling height should expect to see half or less of the earth's surface below, as a result of clouds at that height in addition to lower clouds.

The cloud observational requirements developed for AOS by AWS are listed in Table 1 and also shown in Figure 1. Ceiling is generally required to be measured to an accuracy of 10 percent or less of the height above the ground, while the tops of clouds are generally required to be measured to within 20 percent of the height above ground. These requirements are comparable to the accuracy of RBC measurements up to about 2000 ft and of higher accuracy at greater heights. Sky condi-

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1. Brousaides, F.J. (1983) An Assessment of the AN/GMQ-13 Cloud Height Set Capability to Meet AWS Requirements, AFGL-TR-82-0382, AD A127516.

2. Petrocchi, P.J., and Paulsen, W.H. (1966) Meteorological significance of vertical density profiles of clouds and precipitation obtained with the AN/TPQ-11 Radar, Proc. 12th Radar Meteorol. Conf., Am. Meteorol. Soc., Boston, 467-472.

3. Paulsen, W.H., Petrocchi, P.J., and McLean, G. (1970) Operational Utilization of the AN/TPQ-11 Cloud Detection Radar, AFCRL-TR-70-0335, AD 709364.

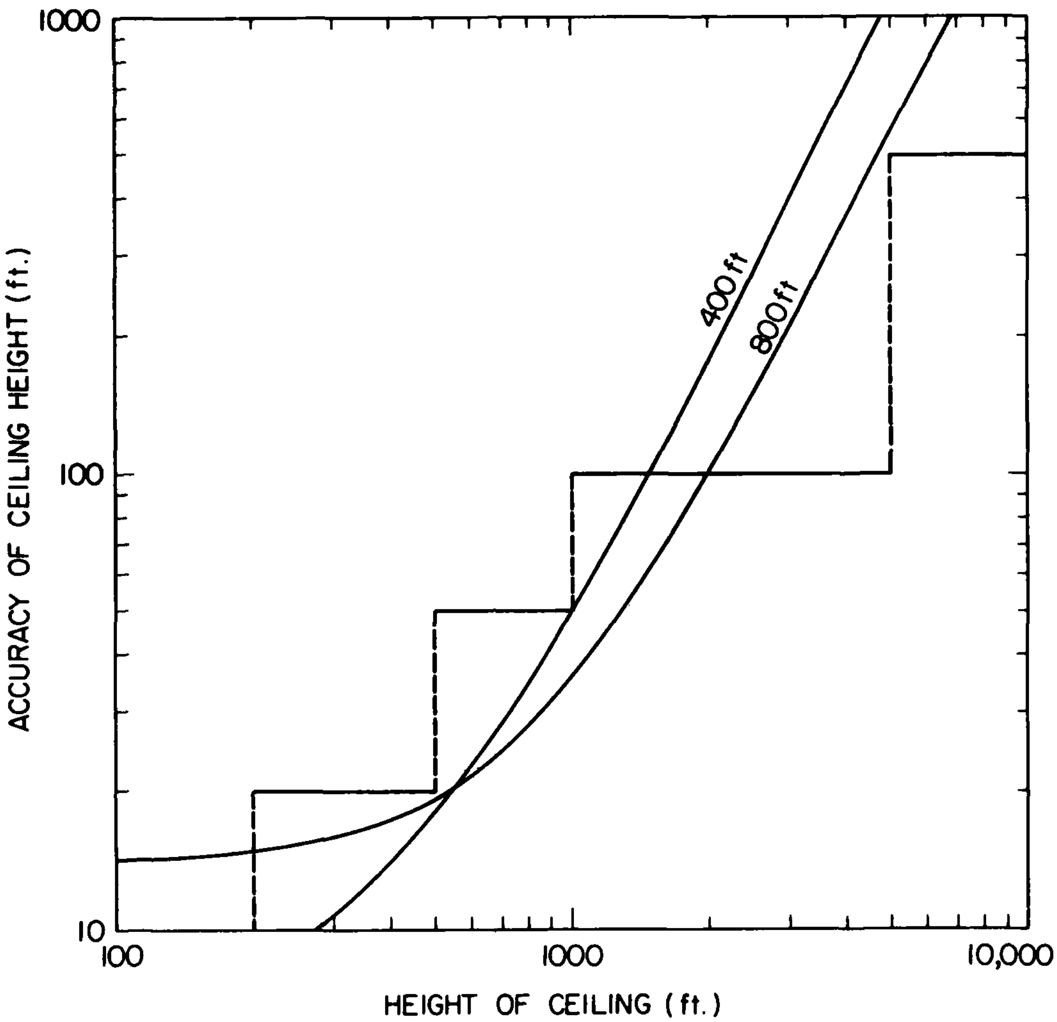

Figure 1. Accuracy of Ceiling Height Measurements by RBC Compared With Accuracy Required for the AOS. Beam tracking error of 1 degree is assumed for the RBC, and accuracy is illustrated for 400-ft and 800-ft baselines

tion is a requirement of lesser priority, but the specification of ceiling implies an evaluation of fractional sky coverage at each cloud layer. In addition to the quantitative observations, there are requirements of lower priority for specification of certain cloud types, such as stratus, stratocumulus, towering cumulus, virga, etc., and the specification of ceiling or sky condition at a distance from the station if different from conditions at the station.

Table 1. Requirements for the Automated Observation of Clouds

Height of cloud layer (ft, above ground level)	Accuracy (ft)
0-200	±10
201-500	±20
501-1000	±50
1001-5000	±100
5001-10,000	±500
10,001-20,000	±1000
20,001-30,000	±2000
Above 30,000	±2500
Height of cloud top	
0-2500	±500
Above 2500	±20%
Cloud amount	
0/10-10/10	±1/10

In the following section, we discuss criteria for the detection of clouds and review the capabilities of several types of remote sensing devices. Examples of measurements by radar and lidar are cited. We discuss some of the problems related to observational procedures. Finally, we offer recommendations for further development of techniques for automated cloud observation.

2. REMOTE SENSING OF CLOUDS

The requirements for measuring cloud tops and the base heights of upper cloud layers virtually require the use of a microwave system, since optical and infrared signals have limited capability to penetrate clouds. These latter types of sensors do merit consideration for ceiling measurement, as their sensing capability most closely approximates the capability of a human observer. We begin by presenting the equations that define the detectability of meteorological backscatter signals and applying these to pulsed and continuous wave (CW) radars operating at wavelengths of 8.6 mm (K_a-band) and 3.2 cm (X-band). We discuss the capabilities of existing K_a- and X-band radars relative to cloud detection requirements. Finally, we present some merits and deficiencies of optical and infrared systems.

We have not discussed the merits of 1.8 cm (K_u-band) radar, which may represent a desirable compromise between longer and shorter wavelengths, nor have we discussed the possible use of pulse compression techniques.

2.1 Detection Criteria

A convenient form of the radar equation for meteorological targets is[4]

$$\overline{P}_r = \frac{\pi P_t A_e \Delta R \eta}{64 R^2} \tag{1}$$

or

$$\overline{P}_r = \frac{\pi^6 P_t A_e \Delta R |K|^2 Z}{64 \lambda^4 R^2} \tag{2}$$

where $\overline{P}_r$ is the average received power, P_t the transmitted power (peak in a pulsed system, and average in a CW system), A_e the effective antenna aperture, ΔR the range resolution, η the reflectivity (cross section per unit volume), R the range, $|K|^2$ the dielectric factor in the particle cross-section, λ the wavelength, and Z the reflectivity factor, equal to the summation of the sixth powers of particle equivalent diameters (proportional to the summation of the Rayleigh backscatter cross-sections). The system noise is assumed to be given by $k\, T_{op}\, B_N$, where $k = 1.38 \times 10^{-23}$ J K^{-1} is the Boltzmann constant, T_{op} the effective operating temperature of the receiver, and B_N the receiver bandwidth.

In a pulsed system, $\Delta R = c\tau/2$, where c is the speed of light, τ is the pulse width, and B_N is approximately equal to $1/\tau$. Thus, the minimum reflectivity factor detectable by a noncoherent pulsed radar (assuming $\overline{P}_{r,\, min} = k\, T_{op}\, B_N$) is

$$Z_{min} = \frac{128 R^2 k T_{op} \lambda^4}{\pi^6 |K|^2 P_t A_e c \tau^2} \tag{3}$$

If the signal power has a Gaussian distribution in the Doppler velocity domain, with standard deviation σ_v, then the peak spectral density is $\overline{P}_r / ((2\pi)^{1/2} \sigma_v)$. If the noise is white, then it has a uniform distribution in the velocity domain $\pm \lambda/(4T)$, where T is the interpulse period. Under these conditions, the minimum detectable

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4. Strauch, R.G. (1976) Theory and Application of the FM-CW Doppler Radar, Ph.D. thesis, U. of Colorado, Boulder.

reflectivity is multiplied by the factor $2T\ (2\pi)^{1/2}\ \sigma_v/\lambda$, which is typically much less than unity. Averaging of successive spectra reduces the variation in the estimates of noise and thus decreases the minimum detectable reflectivity by the inverse square root of the number of spectra averaged. The number averaged in a total observation time T_o is defined by $\lambda/(2T_o\Delta v)$, where Δv is the velocity resolution, which is inversely proportional to the length of time series used in the spectral computation.

In a frequency-modulated continuous-wave (FM-CW) radar, the reflectivity profile is derived by a spectrum analysis of the signal output from the mixer, in which frequency, that is, the beat frequency between the transmitted and received signals, is proportional to range. A spectrum computed from a single sweep of frequency modulation yields a profile of reflectivity which may be biased in range because of the motions of the scatterers. A single spectrum computed from multiple sweeps is typically multi-modal, comprising a Doppler velocity spectrum in each range-resolution increment. Range and velocity resolution and unambiguous range and velocity limits are determined by the parameters of frequency modulation and signal sampling. Strauch[4] notes that the spectral processing is a form of coherent integration and that one result of the spectral processing is that the minimum detectable reflectivity is independent of the frequency modulation bandwidth.

If spectra computed from single sweeps are averaged to derive a reflectivity profile, then the minimum detectable reflectivity factor is given by[4]

$$Z_{min} = \frac{128\ R^2\ k\ T_{op}\ \lambda^4}{\pi^6 |K|^2\ P_t\ A_e\ \Delta R\ (TT_o)^{1/2}} \tag{4}$$

where T is the frequency sweep duration. The range resolution is defined by

$$\Delta R = cT\ \Delta f_s/(2B)$$

where Δf_s is the spectral frequency resolution and B the sweep bandwidth. On the assumption that $\Delta f_s = 1/T$, we have

$$\Delta R \approx c/(2B).$$

Resolution of 3 m, as required below 200 ft (60 m) altitude implies a bandwidth of 50 MHz, while resolution of 100 m, which is less than the required resolution above 5000 ft (1524 m), implies a bandwidth of 1.5 MHz.

Strauch[4] also showed that, because of the distributions of signal and noise in the frequency domain, that is, in velocity and in range, the sensitivity is reduced

if the FM-CW radar is used in a Doppler mode, that is, if the spectrum is computed from a series of sweeps of the transmitted frequency. The minimum detectable reflectivity in the Doppler mode is given by[4]

$$Z_{min} = \frac{256\, R^2\, k\, T_{op}\, \sigma_v\, \lambda^4}{\pi^5 \sqrt{\pi}\, |K|^2\, P_t\, A_e\, \Delta R\, (\lambda\, \Delta v\, T_o)^{1/2}} \tag{5}$$

where Δv is assumed to be less than σ_v.

The FM-CW radar in a Doppler mode is significantly less sensitive than in a conventional mode, especially at shorter wavelengths because of the square root of wavelength in the denominator of Eq. (5). However, it should be recognized that Doppler processing will be of greatest value when precipitation-sized particles are present, and reflectivity is therefore much higher than that associated with clouds.

2.2 K_a-Band Radar

2.2.1 MAGNETRON TRANSMITTER

AWS acquired a substantial amount of operational experience with the TPQ-11 radar, operating at 8.6 mm wavelength, between 1964 and 1975.[2,3] This radar was utilized primarily for detection of ceiling layer height and secondarily for subjective evaluation of cloud layer structure. The high power magnetron (100 kw peak) used in the TPQ-11 had a rather short operating lifetime and was expensive to replace. The poor reliability and high cost of maintenance ultimately resulted in the removal of this radar from operational status.

In considering this wavelength for a new automated cloud sensor, we seek to determine (1) whether current transmitter technology will permit a more reliable system, and (2) whether current data processing technology will enable more effective use of radar data acquired in either a fixed or a scanning antenna mode. During the past six years, experience with K_a-band meteorological radars has been acquired by the Wave Propagation Laboratory (WPL) of the National Oceanic and Atmospheric Administration (NOAA)[5] and the University of Washington.[6] Both organizations acquired and modified surplus TPQ-11 radars in 1979, and WPL

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5. Pasqualucci, F., Abshire, N.L., Chadwick, R.B., and Kropfli, R.A. (1980) Cloud observations during the PHOENIX Experiment, Preprints 19th Conf. Radar Meteorol., Am. Meteorol. Soc., Boston, 715-717.

6. Weiss, R.R., Sr., Locatelli, J.D., and Hobbs, P.V. (1979) Simultaneous observations of cloud and precipitation particles with vertically pointing X-band and K_a-band radars, IEEE Trans. Geosci. Electronics, GE-17: 151-153.

built a coherent, fully scanning, dual polarization, K_a-band radar which was first operated in 1981.[7] The dual polarization capability was incorporated to measure the shape and orientation of cloud and precipitation particles in the context of cloud physics research. Subsequently, Aeromet, Inc., of Tulsa, Okla., built a coherent dual polarization radar, modeled on the WPL radar, for airborne observations of clouds and precipitation.

All these radars use magnetron transmitters; those of the radars built by WPL and Aeromet are similar, but not identical, to that of the TPQ-11. The TPQ-11 transmits pulses of about 100 kW peak power and 0.5 μsec width at a rate of 1000 Hz. The K_a-band radar built by WPL transmits pulses of 160 kW peak power and 0.25 μsec width at an average rate of 2000 Hz. An intermediate frequency signal obtained by mixing the magnetron and local oscillator outputs is used to phase lock the coherent oscillator. Coherency is difficult to maintain, partly because of the narrow pulse and partly because of frequency drift of the magnetron. (The WPL TPQ-11 radar is not coherent.) The University of Washington found this approach unreliable and achieved coherency in its TPQ-11 by a different technique, one in which the phase of the magnetron output is sampled and then compared in digital processing with the phase of the received signals in successive gates. While the operators of these radars claim a moderate to high degree of reliability and an excellent capability for detection of clouds, it should be recognized that these are research radars, operated in a closely monitored environment. Magnetron lifetime of 500-1000 hours, by WPL estimate, would tend to preclude their use in an Air Force operational environment.

The minimum reflectivity detectable by the radar built by WPL is about -29 dBZ at 10-km range,[7] which is considered adequate for the detection of most visible clouds at vertical incidence. The comparable figure for the TPQ-11 at the University of Washington is about -23 dBZ. A recent comparison of measurements by this TPQ-11 and an instrumented aircraft showed that very thin nonprecipitating clouds of water content less than about 0.10 $gm\ m^{-3}$ (reflectivity less than -36 dBZ) could not be reliably measured by the radar at 1-km range, although clouds as much as 7 dB less reflective could generally be detected qualitatively on the radar A-scope display.[8] This comparison also included measurements by a 5.5-cm wavelength (C-band) radar. At rainfall rates of 1.5 to 4.6 $mm\ hr^{-1}$, the TPQ-11 radar yielded reflectivity estimates 10 to 18 dB lower than those of the C-band

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7. Pasqualucci, F., Bartram, B.W., Kropfli, R.A., and Moninger, W.R. (1983) A millimeter-wavelength dual-polarization Doppler radar for cloud and precipitation studies, J. Clim. Appl. Meteorol. 22:758-765.

8. Hobbs, P.V., Funk, N.T., Weiss, R.R., Sr., Locatelli, J.D., and Biswas, K.R. (1985) Evaluation of a 35 GHz radar for cloud physics research, J. Atmos. Oceanic Tech. 2:35-48.

radar. Attenuation in the rain was thought to account for no more than 6 dB of attenuation; the source of the additional attenuation was not identified. Attenuation of these magnitudes could lead to errors of 0.5 to 1 km (1600 to 3300 ft) in the specification of cloud top height from a measurement at vertical incidence, depending on the detailed reflectivity structure. Measurements at oblique incidence, typically having a longer path length through precipitation, would be subject to greater errors.

In an operational sensor, one could envision an attenuation correction based on independent measurement of rainfall rate and height of the 0° C isotherm and a nominal relationship of attenuation to rainfall rate. Such a correction would be unreliable in convective precipitation, since precipitation rates would be typically higher, the relationship to attenuation more variable, and super-cooled liquid water above the 0° C isotherm would contribute significantly to attenuation.

2.2.2 SOLID STATE TRANSMITTER

Two alternatives to the pulsed magnetron transmitter have been suggested: (1) a pulsed transmitter using a solid state signal source with a traveling wave tube (TWT) or "twystron" (combined TWT and klystron) amplifier, and (2) a low power FM-CW transmitter. A TWT amplifier was used in an instrumentation radar built by Lincoln Laboratory that has been operated at Kwajalein Missile Range since 1983. This radar transmits frequency-modulated pulses of 30 kW peak power and 50-μsec width at a rate of 2000 Hz. While the large (13.7-m diameter) antenna makes this radar unsuitable for short range measurements, it should yield valuable information on the operating characteristics of the TWT, the solid state source, and the pressurized waveguide components.

The FM-CW transmitter alternative circumvents the problems associated with waveguide pressurization and high power signals. Other factors become important in such a system, including linearity of the frequency modulation, stability of the frequency from sweep to sweep, higher noise level caused by the required wide bandwidth of the receiver, and the need for on-line spectrum analysis to recover the reflectivity profile. Ford Aerospace and Communications Corporation designed and patented such a radar[9] and implemented the design in a "breadboard" system transmitting 10 mW. Ford estimated that 200 mW would be required for operational cloud detection. If discrimination between cloud and precipitation is essential in an automated system, then it may be necessary to incorporate a Doppler capability following the technique described by Strauch[4] and implemented at 10.7-cm wavelength (S-band). The sensitivity of such a radar can be evaluated with Eq. (4). Using R = 10 km, T_{op} = 527 K (4.5 dB noise figure), λ = 8.6 mm,

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9. Cribbs, R.W., Lamb, B.L., and DeLacy, T.J. (1981) Swept Frequency Radar System Employing Phaseless Averaging, U.S. Patent 4,268,828.

$|K|^2 = 0.90$ (liquid water), $P_t = 200\,mW$, $A_e = 1.57\,m^2$ (2-m diameter and 50 percent efficiency), $\Delta R = 100\,m$, $T = 50\,msec$, and $T_o = 1\,sec$, we have

$$Z_{min} = 8.38 \times 10^{-5}\ mm^6\ m^{-3}$$

or

$$10 \log Z_{min} = -40.8\,dBZ.$$

This minimum detectable reflectivity is considered sufficient for detection of nearly all clouds, and the operational parameters are comparable to those used or suggested for use in radar systems. The radar sensitivity in the Doppler mode can be evaluated by Eq. (5). Using $\sigma_v = 1\,m\ sec^{-1}$, $\Delta v = 0.25\,m\ sec^{-1}$, and other values identical to the previous calculation, we have

$$Z_{min} = 1.43 \times 10^{-3}\ mm^6\ m^{-3}$$

or

$$10 \log Z_{min} = -28.4\,dBZ.$$

A K_a-band FM-CW radar could detect nearly all clouds to a range of about 10 km. The transmitted bandwidth and sweep time and the data sampling and processing parameters can be varied to yield range resolution and sensitivity adequate to meet the observational requirements.

2.3 X-Band Radar

Radars of 3-cm wavelength have not generally been considered viable for cloud detection (in the absence of precipitation) because of the much smaller backscatter cross-section of hydrometeors at this wavelength. In the Rayleigh approximation, the reflectivity η (cross section per unit volume) is proportional to λ^{-4}, so that the reflectivity at 3 cm is about 1/148 that at 8.6 mm, or about 22 dB less. This loss of detection capability relative to K_a-band can be offset by an appropriate choice of radar parameters and data processing techniques. Advantages of this frequency include negligible attenuation except in moderate or greater rainfall, and anticipated lower cost and higher reliability of microwave components. Disadvantages include large size of components, particularly if a scanning sensor is implemented, and the uncertainty of detecting thin or tenuous clouds. Ground-based meteorological radars operating at this wavelength are all pulsed systems, transmitting pulses with peak power 30 to 250 kW and pulsewidths between 0.25 and

5.0 μsec. Minimum reflectivity detectable by these systems is typically between -11 and +3 dBz at 10 km range, corresponding to a mist with precipitation rate about 0.005 mm hr^{-1} or less.

Comparisons of measurements by K_a-band and X-band radars have been reported by WPL[10] and the University of Washington.[6] While each of these comparisons shows the superiority of the respective K_a-band radar for cloud detection, they also provide a baseline from which improved detection capability can be projected. The Washington radars transmitted identical peak powers (80 kW) at identical pulse repetition frequencies (1000 Hz) with similar pulse widths, but with larger antenna aperture and beamwidth at X-band than at K_a-band. The X-band radar was found to be about 26 dB less sensitive than the K_a-band radar, mainly because of the wavelength dependence of the reflectivity. In seeking to increase the sensitivity of X-band radars, we consider changes in the microwave components, the receiver, and the data processing system. For example, with reference to the radar used by the University of Washington, a 20-dB increase in sensitivity could be realized easily by increasing transmitted power (from 80 to 250 kW), pulse width (from 0.4 to 1.0 μsec), and antenna diameter (from 3 to 4 m) and decreasing the minimum detectable power (from -94 to -104 dBm). Because of the high resolution ceiling measurements required for the present application, however, the increased pulse width is undesirable. Hence, the required improvement in detection capability implies the need for some 10 dB or more of signal-to-noise enhancement in data processing.

A form of coherent integration of the received signal seems most promising for this purpose. In a pulsed system, coherent integration can be accomplished either through computation of the Doppler velocity spectrum or through averaging of successive samples of the complex received signals. These techniques are combined in the vhf and uhf radars used to observe backscatter from refractive index inhomogeneities in the clear atmosphere.[11] In this application, with a wavelength of 7.4 m, for example, the decorrelation time of the medium is about 0.25 sec, so that, with a pulse repetition rate of 6250 Hz, some 240 samples can be obtained while the scattering medium remains essentially coherent. These are then averaged to yield a single complex sample with the effective signal-to-noise

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10. Pasqualucci, F., and Miller, L.J. (1981) Dual wavelength radar observations in clouds and precipitation, Preprints 20th Conf. Radar Meteorol., Am. Meteorol. Soc., Boston, 574-578.

11. Green, J.L., Gage, K.S., and Van Zandt, T.E. (1979) Atmospheric measurements by VHF pulsed Doppler radar, IEEE Trans. Geosci. Electronics GE-17:262-280.

ratio increased in proportion to the number of pulses averaged. A succession of these averaged data are then used to compute a Doppler spectrum.

Use of these techniques in an X-band system observing clouds is restricted by the shorter decorrelation time of the medium (typically 5 to 10 msec). At the pulse repetition rate of 10,000 Hz (with an unambiguous range interval of 15 km), one can obtain perhaps 5 to 10 samples while the medium is essentially coherent, yielding an increase of about 5 dB in sensitivity. This increase is unreliable, however, as it depends on both the mean Doppler velocity of the scattering medium and the Doppler spectrum variance.

A more reliable approach would be to compute Doppler spectra in multiple range gates, using a fast Fourier transform (FFT), and then to average several spectra to reduce fluctuations in the noise spectrum and enhance the detectability of the signal spectrum. The spectral computation changes the minimum detectable signal by the factor $2T\,(2\pi)^{1/2}\,\sigma_v/\lambda$, as noted above. With $T = 500\ \mu$sec, $\sigma_v = 1$ m sec^{-1}, and $\lambda = 3.2$ cm, this factor is 0.084, corresponding to a decrease of 10.8 dB. The minimum detectable signal is multiplied by $(\lambda/(2T_o\,\Delta v))^{1/2}$ because of the averaging of the spectra. With $T_o = 1$ sec and $\Delta v = 0.25$ m sec^{-1}, this factor is 0.24, corresponding to a decrease of 6.1 dB. With parameters $R = 10$ km, $T_{op} = 527$ K, $\lambda = 3.2$ cm, $P_t = 250$ kW, $A_e = 3.53\ m^2$ (3-m diameter and 50 percent efficiency), and $\tau = 0.1\ \mu$sec, we have from Eq. (3)

$$Z_{min} = 0.041\ mm^6\ m^{-3}$$

or

$$10 \log Z_{min} = -13.8\,\mathrm{dBZ}.$$

The additional sensitivity introduced by spectral processing and noncoherent integration yields

$$10 \log Z_{min} = -30.7\,\mathrm{dBZ}.$$

The pulse width used here yields a rangewise resolution of 15 m (49 ft), which meets the AOS requirements above 500-ft altitude. Additional sensitivity for high-altitude cloud detection could be achieved by integration in range. While sensitivity at short range is adequate, use of a narrower pulse for higher resolution would seriously degrade sensitivity at all ranges.

Employing an FM-CW transmitter at X-band, as at K_a-band, is an attractive alternative. Using Eq. (4) with $R = 10$ km, $T_{op} = 527$ K, $\lambda = 3.2$ cm, $|K|^2 = 0.93$,

P_t = 400 mW, $A_e = 3.53\,m^2$, ΔR = 500 m, T = 50 msec, and T_o = 1 sec, we have

$$Z_{min} = 6.9 \times 10^{-4}\ mm^6 m^{-3}$$

or

$$10 \log Z_{min} = -31.6\,dBZ.$$

With these same parameters, except ΔR = 30 m and R = 1 km, the radar could theoretically detect -39.4 dBZ. Thus, the FM-CW X-band radar could theoretically detect most clouds with the required resolution at all altitudes.

There are practical issues with all radars, relating to short-range measurements. If a single antenna is used for transmitting and receiving in a pulsed system, then the receiver must be isolated from the high-power pulse, with a typical recovery time of about 1 μsec. In an FM-CW system, the receiver must likewise be isolated, for example, by a well designed circulator in combination with filtering of that part of the transmitted signal that leaks into the receiver. In a dual-antenna system, such as the TPQ-11, the beams are only partially overlapped at short range, resulting in a loss of detection capability.

2.4 Lidar

The principal advantage of an optical or infrared sensor for the present application is that the response of such a sensor is most similar to the response of the eye. A lidar thus offers the possibility of discriminating a true ceiling from a partial obscuration at a lower altitude more readily than could be done with radar observations. Another advantage of lidar systems, relative to the required accuracy of ceiling measurements at low altitude, is the narrow pulse widths characteristic of these systems. Comparisons between lidars and radars illustrate the excellent capability of lidars for detecting cloud bases. A lidar of 0.694-μm wavelength and 30-nsec pulse width (15-ft resolution) was compared with the modified TPQ-11 radar at WPL.[12] During observations of a stratus cloud layer with imbedded precipitation, the two measurements of cloud base were within ±300 ft except when the cloud base was varying rapidly in time, for example, more than about 1000 ft in a minute or less. Cloud top sensed by the lidar was 600 to 1200 m (2000 to 4000 ft) lower than that indicated by the radar. A comparison between a

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12. Pasqualucci, F., and Abshire, N.L. (1980) A comparison of cloud top and cloud base measurements by lidar and 8.6-mm radar, Preprints 19th Conf. Radar Meteorol., Am. Meteorol. Soc., Boston, 718-721.

lidar of 0.694-μm wavelength and 10-nsec pulse width (4.5-ft resolution) and a radar of 1.79-cm wavelength (K_u-band) was conducted at the University of Utah.[13] These observations were in altostratus clouds of peak reflectivity generally less than 20 dBZ and of 1- to 2-km vertical extent in which precipitation was developing. Attenuation of the lidar signal was evident wherever the radar reflectivity exceeded about 10 dBZ, and cloud tops indicated by the lidar were 300 m or more below those indicated by the radar.

The issue of eye safety may limit the use of a lidar in an automated cloud detection system. However, a lidar operating at safe power levels could be useful for measuring very low ceilings with the required accuracy.

3. OBSERVATIONAL PROCEDURES

The foregoing section presented technical issues pertaining to the cloud sensor, relative to the capabilities of detecting the distance to the nearest cloud and of measuring the rangewise extent of clouds, for example, through a rangewise profile of radar reflectivity. This section addresses issues of observational procedure, focusing on sampling strategy, analysis procedures, and update intervals. Time is a critical factor, in that the required hourly reports should approximate the sky conditions near the times of the reports rather than extended averages of conditions during the intervening times. In addition, if ceiling or sky conditions change significantly between successive hourly reports, a special report is required. Such changes should be indentifiable by the sensing system within a few minutes, at most, corresponding to the capability of a human observer.

The simplest sensor configuration involves a single, fixed, vertically pointing beam, yielding successive vertical profiles of cloud structure over the observing point. While this configuration might be ideal as an aid to a human observer, it provides an uncertain capability for fully automated cloud observation because of the difficulty of characterizing the fractional coverage at any given height. Estimation of cloud cover must be based on a series of samples extending for sufficient time to allow a representative sample of the cloud layer to advect through the beam. As an example, we consider the problem of estimating cloud conditions within an airport traffic area (5 statute miles radius). An appropriate sampling duration could be equal to the diameter divided by the wind speed at the height of the cloud layer. Even if one accepts half this time as adequate, the sampling time exceeds 15 min at wind speeds less than 20 kt (10 m sec^{-1}). If the cloud structure

13. Sassen, K. (1983) Comparisons of K_u-band radar and polarization lidar returns from orographic clouds, Preprints 21st Conf. Radar Meteorol., Am. Meteorol. Soc., Boston, 242-245.

is significantly non-homogeneous, for example, rows of stratocumulus, then a one-dimensional sample may not yield a correct estimate of fractional coverage.

The most comprehensive observation of the sky requires a fully scanning sensor to document the distribution of clouds throughout the volume of interest, for example, from the surface to 40,000 ft within a 5-mi radius of the observation point. Because the requisite sensitivity of the system will probably preclude rapid scanning, it is likely to require 15 minutes or more to complete such a scan sequence. Under certain conditions, the scan sequence could be abbreviated; such conditions could be identified by analysis of a "full-volume" scan or specified on the basis of a limited set of measurements. In general, a full-volume spatial sample should not be necessary, as the objective is to characterize the base, top, and fractional coverage of each cloud layer and not to attempt to identify each cloud element.

The limitations of scanning systems were addressed in considerable detail in a 1971 study sponsored by the Federal Aviation Administration (FAA) and NOAA.[14] This study included an analysis of the roles of temporal and spatial averaging, based on a number of vertically pointing sensors, and compared the performance of a scanning sensor with that of an equivalent number of vertically pointing sensors. The most serious problem arises when the clouds are very low and scans at low elevation angles are required for meaningful spatial sampling. Small increments of elevation angle are required for effective spatial sampling of low cloud layers. In addition, such measurements are likely to suffer in accuracy of cloud height because of the finite beamwidth of the sensor. The possible restriction on spatial sampling of low cloud layers implies not only increased standard deviation of the ceiling estimate, but also limited capability to detect the approach of low cloud layers at a distance from the observing point. Natural variability of the cloud base may limit the useful accuracy with which the ceiling can be specified. These and related issues must be addressed as part of the continuing development effort.

4. SUMMARY AND RECOMMENDATIONS

Sensor technology to be considered for AOS cloud observation requirements includes K_a-, K_u-, and X-band radars and optical and infrared lidars.

There is a substantial base of experience and data from K_a-band radars, in-

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14. Duda, R.O., Mancuso, R.L., and Paskert, P.F. (1971) Analysis of Techniques for Describing the State of the Sky Through Automation, FAA-RD-71-52, AD 735213.

cluding recent developments and the current use of K_a-band radars in meteorological research. Existing data bases should be used to evaluate capabilities for radar detection of clouds, and, in particular, to relate these observations to independent observations of cloud height.

K_u-band radars have seen very limited use in meteorological measurements, and the few existing systems are of relatively low power. A K_u-band system could be a satisfactory compromise between the higher sensitivity, higher component costs, and higher attenuation of K_a-band, and the greater reliability, lower costs, lower attenuation, and lower backscatter cross-sections at X-band. This possibility should be investigated in a design study, with particular emphasis on cost and reliability factors.

Existing X-band meteorological radars are not capable of detecting precipitation-free clouds and hence cannot be used for feasibility studies, except with extensive modifications. This wavelength is a possible choice for a cloud observation system, however, provided that the receiver and data processing system incorporate the maximum use of signal integration to enhance sensitivity.

Lidar is of use only in the detection of cloud base because of the strong attenuation of optical and infrared signals in clouds. Its role in an automated system would probably be limited to low-altitude measurements, where high resolution is required, and it should be considered only if microwave systems cannot provide the cloud base measurements with sufficient accuracy.

In addition to the sensor design study, an effort should be made to use existing data bases and existing radars in the development of techniques for identifying and evaluating cloud structure. This effort should include investigation of the relationship of parameters derived from radar measurements and those derived by other means, for example, airborne observations or RBC measurements. This effort should also address issues such as the discrimination of precipitation from cloud and the identification of the ceiling layer through a low obscuration or low scattered cloud layer.

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